Preliminary Analysis of Median Grain Size and Armoring Comparisons From Field Studies in Oregon & Washington

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ABSTRACT

Field surveys in headwater channels in the Pacific Northwest reveal a systematic downstream coarsening and show evidence for a strong hydraulic control on median bed-surface grain sizes. In contrast, subsurface median grain sizes exhibit no downstream trends. Our data further show that local sediment sources can change the degree of channel armouring defined by the ratio of the median surface to median subsurface grain size, and thereby swamp downstream trends. Our results document a strong context dependence to surface/subsurface grain size ratios and show that the simple surface/subsurface grain size ratio is a unique indicator of neither sediment supply, nor stream health. Both local and watershed context matters to the use and interpretation of such ratios in stream channel assessments.

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INTRODUCTION

Development of a coarse surface layer (typically referred to as a pavement or armour) characterizes channels with coarse-grained beds composed of mixed grain sizes (Parker and Klingeman, 1982). An armored layer forms when differential transport removes the finer particles, leaving behind a coarse 'lag' of clasts more resistant to scour and bed load transport than the original deposit (Knighton, 1984). Features that influence the formation of a coarse surface layer include particle size distributions of the original deposit, sediment loading (both rate and quantity), discharge, flow depth, and channel slope. Downstream fining of the bed-surface grain size is another fundamental characteristic of rivers due to both the factors discussed above and comminution of particles during downstream transport (Gilbert, 1914; Hack, 1957; Leopold et al., 1964). The development of bed-surface textures in mountain channels reflects bed armouring and downstream fining, and therefore hydraulic influences, as well as sediment delivery and routing.

Many studies document downstream patterns in stream-bed texture and armouring in relatively low-gradient, gravel-bed channels (e.g., Church et al., 1987; Lisle and Madej, 1992; Lisle, 1995; Ferguson et al., 1996; Rice, 1999), but there has been little work on such patterns in headwater channels. Flume studies have established that decreased sediment supply leads to enhanced bed surface armouring (Andrews and Parker, 1987; Dietrich et al., 1989), and that selective transport can lead to downstream fining (Paola et al., 1992; Seal et al., 1997). In some of the few field studies of headwater channels in mountain drainage basins, Miller (1958) found a strong lithologic control on grain size and little evidence for systematic downstream fining in New Mexico; Montgomery and Buffington (1997) found evidence for a correlation between bed surface grain size distributions and stream bed morphology in the Pacific Northwest; and Buffington and Montgomery (in press,a,b) showed that both sediment supply and roughness elements (bedforms, banks, and obstructions such as wood debris) systematically affect bed-surface grain sizes. As both field and flume studies indicate that the degree of bed armouring responds to changes in watershed processes (e.g., discharge and sediment supply), it is not surprising that various measures of the degree of bed-surface armoring have been proposed as methods for determining sediment loading (Dietrich et al., 1989; Buffington and Montgomery, in press,b) or as indicators

of stream 'health' in channel assessment procedures. Here we examine both local and watershed-scale relationships between bed-surface grain size, the degree of armoring, and hydraulic features for small channels in Oregon and Washington.

THEORY

Bed-surface grain sizes could reflect either local hydraulic controls on armour development (the hydraulic hypothesis), the effects of local sediment supply (the supply hypothesis), or the downstream comminution that results from clast wear and abrasion (the comminution hypothesis). While all three of these processes affect bed surface textures in rivers, their relative effects are not well established for mountain streams. The signature of comminution should be a systematic downstream fining of bed-surface material with distance traveled, and hence a decline in median bed-surface grain size (d_{50}) with increasing drainage area. A strong hydraulic control on bed-surface grain sizes would result in a relation between d_{50} and hydraulic variables related to the shear stress exerted on the stream bed or the stream power of the flow. In contrast, a strong control of local sediment supply would contribute to masking either of these hypothesized relationships, and hence no relationship between d_{50} and either drainage area or hydraulic variables.

Shields (1936) proposed that sediment movement occurs when the shear stress exerted on a particle exceeds the resisting stress. This critical shear stress is proportional to grain size, while the resisting shear stress is related to the hydraulic radius or mean channel depth (D) and channel slope (S). This relation can be expressed by the Shields equation, which can be rearranged and simplified to yield:

$$d_{50} = (DS/\tau^*_c)\,(\rho_w/(\rho_s-\rho_w)) \tag{1}$$

where τ^*_c is the dimensionless critical shear stress, and ρ_s and ρ_w are the density of sediment and water, respectively. Hence, a shear stress control on bed surface texture predicts that the median grain size is proportional to the depth-slope product. Although it is common to use bankfull flow

depth to approximate the critical shear stress, the bankfull depth can be difficult to evaluate in mountain channels.

The stream power of a reach (Ω) is proportional to the product of discharge and slope (e.g., Bull, 1979):

$$\Omega = \rho_w \, g \, Q \, S \tag{2}$$

Substituting the approximately linear relation between drainage area and discharge (Dunne and Leopold, 1978), equation (2) can be recast as

$$\Omega = k \, A \, S \tag{3}$$

where k is a contant. Hence, if bed surface grain size is controlled by hydraulic properties of the flow or the general bed load transport capacity, then d_{50} should be a function of the product of either flow depth and slope, or drainage area and slope.

STUDY AREAS

Surface and subsurface sediment size data were collected in Finney Creek, Boulder River, and South Fork Hoh River in Washington State and three basins collectively referred to as the Coos Bay watersheds in the southern Oregon coast range (Figure 1). The study areas present a range of lithologies, climate history and land use. Comparisons of downstream trends in bed surface grain size among these watersheds illustrates the influence of these factors.

The Finney Creek and Boulder River watersheds are located in the northern Cascade Mountains. Both watersheds are underlain by igneous and metamorphic bedrock, and the lower ends of the basins are covered by extensive glacial deposits. Finney Creek was heavily logged in the 1970s and 1980s and has many local sediment sources both from debris flows and from erosion of glacial deposits. In contrast, the Boulder River watershed is a U.S. Forest Service

Wilderness area. Hence, the Finney Creek and Boulder River watersheds provide a strong contrast in the degree of land management.

The South Fork Hoh River (SF Hoh River) is underlain by unconsolidated marine sediments near the estuary to metamorphic bedrock at its origin on Mount Olympus. Glacial deposits limit exposure of bedrock in the SF Hoh River and provide exotic sediment for transport in the river channels. The headwaters of the SF Hoh River are located within the Olympic National Park and are also covered by virgin timber, but some of the areas in the lower portions of the watershed were clear cut in the late 1980s and 1990s. We divided the surveyed reaches from the SF Hoh River into those where the contributing drainage area or immediate vicinity of the reach had recent timber management (managed) and those where no timber management had occurred either upstream or within the reach (old growth).

The Coos Bay watersheds (Deton, Larsen and Sullivan Creeks) are located in the southern Oregon Coast Range, a few kilometers north of Coos Bay, Oregon. The Tyee Formation, which underlies all three creeks, consists of uplifted Tertiary marine sediments that are mostly sandstone. Unlike the Washington watersheds, these basins were not glaciated. The Coos Bay watersheds consist of industrial forest lands.

METHODS

Field surveys included sediment size measurements conducted in 27 reaches from Finney Creek, 18 reaches from Boulder River, 34 reaches from SF Hoh River and 12 reaches from the Coos Bay watersheds. These reaches have average gradients that range from 0.001 to 0.5 m/m and drainage areas from 0.1 to just over 100 km^2. The channel morphologies of the selected reaches were not significantly influenced by woody debris, except as noted. Data collected during the surveys includes: surveyed longitudinal and cross-sectional profiles, channel morphology, comments on the influence of wood debris, and sediment size measurements. Longitudinal profiles and cross-sectional data were collected using a hand-held level or a tripod mounted engineering level, a stadia rod and a tape. A least-squares linear regression of the long profile data was used to estimate the reach average slopes for most reaches, but a few reach slopes were

calculated by using total elevation gain divided by the length surveyed. Reach locations were mapped onto USGS 7.5' topographic quadrangles. Drainage areas were measured by digitizing watershed boundaries from the topographic quadrangles.

Sediment size measurements included both surface and subsurface pebble counts. We employed the 'Wolman pebble count' methodology (Wolman, 1954) for surface grains, and a modified 'Buffington' methodology (Buffington, 1996) for subsurface grains. The 'Wolman' method consists of selecting the clast next to the left side of the right foot with the point of an index finger; measuring the medial axis of the clast; then stepping forward, and while looking away selecting the next clast. Each Wolman count included measurements of 100 clasts collected in several transects across the sample area. The distance between steps and between transects was field determined based on the size of the sample area and size of the grains in the channel. Samples were collected from both exposed bars and submerged locations within the reaches surveyed.

A modified form of the 'Buffington' methodology was employed for the subsurface sampling. The 'Buffington' method consists of selecting an aerial deposit of sediment within the active channel and proximal to the surface pebble count, removing surface material (by hand) to a depth of one to two times the median grain-size, and exposing approximately 1 m^2 of sub-surface material. The subsurface material was then mixed and 'loosened' to a depth of 15-30 cm. Grains were randomly selected by pointing with a fingertip while looking away from the sample area, whereas the method proposed by Buffington (1996) uses a pencil tip.

Sediment size data was summarized as three measurements for each sample: median grain size (d_{50}) for both surface and subsurface pebble counts, the percentage of sampled grains <2 mm, and a ratio of surface to subsurface median grain size (d_{50s}/d_{50ss}) as a measure of surface armoring. Linear and power regressions are employed for determining 'best-fit' equations for comparisons between hydraulic features, and both grain size and degree of armoring.

RESULTS

Reach surveys for each watershed allow examination of whether trends in measured grain size and armoring conform to the predictions of the channel hydraulics hypothesis. Our analysis of median grain sizes focuses on relationships between drainage area, the depth-slope product, and the drainage area-slope product in each watershed. We explore trends between these physical features described above with the degree of surface armoring for each watershed. We also compare the percentage of fine sediment (<2 mm diameter) between and within watersheds for both surface and subsurface measurements. Results for each watershed are summarized into three plots of d_{50} versus: A) drainage area; B) depth*slope; and C) drainage area*slope.

Finney Creek

Other than channel slope data, which are concentrated below 0.05, drainage area, grain sizes, and depth data are well distributed for the Finney Creek data. Median grain size measurements range from 6 to 110 mm for the surface pebble counts, and 0.5 to 1.3 cm for the subsurface pebble counts. In contrast, most drainage areas were larger than 10^6 m^2 even though drainage areas of the surveyed reaches range from 10^4 to just over 10^8 m^2. Depth-slope product data ranged from <0.01 to 0.05 m but most data were concentrated below 0.02 m. The product of drainage area and channel slope produced a fairly even distribution of data ranging from just over 10^4 m^2 to just over 10^6 m^2.

Surface material characteristics in Finney Creek basin are most related to the depth-slope product, while subsurface clast sizes do not change substantially, regardless of hydraulic characteristics of the reach. Since surface grain sizes vary considerably throughout the watershed, no relationships between particle size and channel characteristics (Figure 2A-C) are apparent. Although the drainage area vs. grain size comparison (Figure 2A) produces the best fit (R^2 of 0.22) for the Finney Creek data, the relationship is not strong. Visually, the best relationship exists between depth*slope and clast size (Figure 2B), however the large variation in grain size greatly degrades the goodness-of-fit for the linear regression (R^2 of 0.10). The comparison of the drainage area-slope product with surface grain size (Figure 2C) does not yield a relationship.

Subsurface grain sizes do not appear to be affected by any channel feature that we measured (Figure 2A-C). These data indicate that both surface and subsurface grain sizes are relatively insensitive to position of the reach in the Finney Creek watershed, and only weakly related to local hydraulic variables.

Boulder River

Data collected in the Boulder River watershed indicates that the range in grain sizes for both the surface and subsurface are similar to those found in the Finney Creek data, but that reaches with medium-sized drainage areas are not fully represented in the data set. Median grain size measurements range from 2.2 to 15 cm for the surface pebble counts, and 0.4 to 1.2 cm in diameter for the subsurface pebble counts. Drainage area data ranged from 10^5 to just less than 10^8 m^2 in Boulder River, however data from reaches with drainage areas between 10^6 and 10^7 m^2 are not well represented. The channel slope data has a fairly even distribution and ranges from just over 0.001 to almost 0.18 m/m. The distributions for the drainage area-slope product and the depth-slope product are also evenly disbursed and their ranges are 10^4 to just under 10^7 m^2 and just over 0 to 0.02 m, respectively.

Data collected in the Boulder River watershed indicates that surface grain size appears to have at least weak relationships to all the channel characteristics in this study. Even though the drainage area data are missing intermediate values, a weak pattern suggests that larger channels have larger median grain sizes (Figure 3A). A better relationship exists between the depth-slope product and grain size (R^2 of 0.35), where deep, steep channels have larger grain sizes than shallow, lower-gradient channels (Figure 3B). A drainage area-slope product relationship indicates the most significant relation to grain size for the Boulder River data with an R^2 of 0.46 (Figure 3C). This relationship indicates that d_{50} is larger in big, steep channels (Figure 3C). Results from the subsurface grain size analysis in the Boulder River watershed were similar to those found in Finney Creek watershed, such that the subsurface material does not relate to the measured channel features (Figures 3A-C).

Coos Bay Watersheds

The Coos Bay watersheds are different than Finney Creek or Boulder River watersheds in that median grain sizes and drainage areas are significantly smaller. Although surface median grain sizes (5 to 60 mm) are much smaller than those found in the Finney Creek or Boulder River data, the subsurface grains are similar, ranging from 2 to 8 mm. The drainage areas in the Coos Bay watersheds range up to only 10^7 m^2. Channel slopes measured in the Coos Bay watersheds range from 0.008 to just over 0.12 m/m, but are concentrated near 0.02 m/m. Depth-slope values, like the slope measurements, are concentrated at the low end of the range (<0.01), but range up to 0.045 m. Drainage area-slope values range from 10^3 to 10^5 m^2, but most are between 10^4-10^5 m^2.

The comparisons between grain size and channel characteristics yielded similar results in the Coos Bay data to those found in the Boulder River data, where the strongest grain size relationship was with the drainage area-slope product. Examining drainage area alone with median grain size (Figure 4A), we find a weak log-normal relationship (R^2 of 0.28), indicating a downstream coarsening, with significant scatter in d_{50} values. Only a slightly stronger relationship is apparent in the depth-slope data supporting the same trends found in the Boulder River, where deep, steep channels have larger particles (Figure 4B). The best relationship with an R^2 of 0.45 results from comparing the combined effects of drainage area and slope with surface median grain sizes (Figure 4C). The general increasing trend concurs with those found in both Boulder River and Finney Creek data. As with the data presented from other watersheds, subsurface grain sizes remain approximately the same regardless of the comparison (Figure 4A-C).

South Fork Hoh River

Of all the data sets presented, the SF Hoh River data has the most data. We lump all reaches that have had any land management either upslope in its watershed or along the reach into the managed land type, thereby considering only 'pristine' old growth as the unmanaged land use type. Surface median grain sizes range from 44 to 125 mm for managed reaches and 25 to 210 mm for old growth channels, where the variation in surface grain sizes is greatest in the old growth data. There is little to no difference between the range in subsurface median grain sizes (3

to 9 mm) between land uses. The drainage areas in the SF Hoh River data are evenly distributed from 10^4 up to just over 10^8 m^2 for managed channels with a fairly even distribution but up to only 10^7 m^2 for the old growth reaches. Channel slopes are also well distributed and range from 0.007 to 0.20 (with one reach slope at 0.43) for the managed channels, and from 0.01 to 0.19 for the old growth. The distributions for the drainage area-slope product and the depth-slope product are also evenly distributed and range from 10^4 to just under 10^7 m^2 and just over 0 to 0.02 m, respectively.

Drainage area-slope product data had the strongest correlation with d_{50} regardless of land use in the SF Hoh River watershed. Investigating drainage area and surface grain size data (Figure 5A) shows a weak relationship for managed reach data (R^2 of 0.15) and a somewhat stronger relationship for unmanaged reaches (R^2 of 0.33). Both relationships indicate that small channels (small drainage area) have smaller grains than large channels (Figure 5A) which is consistent with the other watersheds, except Finney Creek. The scatter present in these data, for both land use types indicates that grain size variations occur through out the watershed. Results from the depth-slope product comparison and surface grain size (Figure 5B) indicate that only weak relationships exist in both land uses. The strongest grain size relationships for the SF Hoh River data are logarithmic relations with the drainage area-slope product. These relationships indicates that smaller, less steep channels have small particle sizes, while large, steep channels have large particles (Figure 5C), however grain size increases more rapidly in large steep channels in the old growth than in the managed channels. Subsurface grain sizes are unaffected in each comparison.

Fine Sediment

The amount of fine sediment sampled in subsurface pebble counts was always higher than the amount sampled in the adjacent surface sample and the amount of fine sediment measured varied greatly both within and between watersheds. In Figure 6, the y-axis is the percentage of sediment less than 2 mm in diameter (fine sediment) with data from all four watersheds separated by surface and subsurface fine sediment and presented on the x-axis. Data were also separated into land use types (managed and old growth) for the SF Hoh River data. While most surface fine sediment amounts are below 10% it ranges up to 30% in the Coos Bay watersheds. Subsurface

fine sediment measurements average around 15%, except in the Coos Bay watersheds where it averages about 30%. Data from the Coos Bay watersheds indicates that these watersheds have more fine sediment than the Washington watersheds.

The surface median grain sizes changed very little when the fine sediment was removed from the data set. However, the subsurface grain sizes, when recalculated without the fine sediment, changed substantially in most reaches. For both Figures 7A and 7B, the original median grain size calculated (from all the data) is on the x-axis. The y-axis contains values of the median grain size recalculated after the fine sediment was removed from the data set. Data on both axes are in centimeters and one-to-one lines are drawn on each graph. A point plotting on this one-to-one line indicates that no change in calculated grain size occurred due to the removal of the fine sediment from the data set. However, a data point lying higher than the line indicates that removal of the fine sediment from the data increased the value for median grain size when re-calculated. Most grain size measurements did not change for the surface samples, in fact, only in two reaches did grain size changed substantially and both had more than 30% fine sediment sampled. However, the re-calculation of median grain sizes in the subsurface pebble counts changed substantially (Figure 7B); nearly all mean subsurface particle sizes increased substantially when the fine sediment was removed from the data.

Armoring

Using the simple ratio of d_{50}(surface) to d_{50}(subsurface) to determine the degree of armoring present in a reach indicates that armoring is at most weakly related to position in some watersheds. Figure 8 displays armoring on the vertical axis as d_{50}(surface)/d_{50}(subsurface), while drainage area in square meters is plotted on the horizontal axis. Armoring values range from 0 to 14 in Finney Creek data up to 30 in the SF Hoh River data. The drainage area ranges up to 10^9 square meters.

The best relationship between drainage area and armoring occurs in the Boulder River data with an R^2 of 0.28 (Figure 8B). This weak relationship indicates that the degree of armoring increases downstream. Except for Finney Creek, which indicates a decreasing trend, all the other

watershed data indicate increasing relationships with drainage area (Figure 8). Although these weak relationships exist, the scatter in the data indicates a substantial range for the degree of armoring in a channel reach for all positions in the watersheds sampled.

In summary, each watershed exhibits relationships between channel hydraulic variables and grain size but no discernable variability in subsurface grain sizes. In the Finney Creek watershed, however, grain size had a weak increasing relationship with the depth-slope product, but no discernible relationships could be made with drainage area or drainage area-slope. The range in drainage area data was incomplete for the Boulder River, yet moderately strong increasing relationships were found with most comparisons. Although most of the Coos Bay reaches were low-gradient, moderately strong relationships were found between all comparisons. The SF Hoh River data for managed lands had moderately strong to strong relationships between grain size and channel characteristics. The strongest relationship found in all the data sets occurs in the SF Hoh River - unmanaged lands (old growth) between grain size and the drainage area-slope product. The median subsurface grain sizes did not vary between watersheds or with any measured hydraulic feature. Although the amount of fine sediment sampled in the pebble counts varied between watersheds, the removal of these data did not significantly alter the calculated surface median grain sizes. No significant relationships existed between surface armoring and the position of a reach in a watershed.

DISCUSSION

Our grain size data from Washington and Oregon indicates that the watershed-wide distribution of median surface particle sizes are related to both local hydraulic features and sediment supply, but that the distribution of median subsurface particle sizes are relatively consistent regardless of watershed or local channel conditions. The collection of grain size data is difficult in channels that have a large range of particle sizes; therefore we discuss the pros- and cons- of a variety of methods that are commonly used. Since watershed scale disturbances (i.e., timber harvest) alter the routing of water and sediment, we discuss differences found between data

collected from managed and unmanaged channels. We also investigate the influence of lithology and geologic history by comparing data collected in the Coos Bay watersheds with the data from the other watersheds. Finally, we will discuss the implications of using these kinds of data for determining channel conditions.

Sediment Sampling

We considered two sampling methods for determining the median grain size of a deposit: surface and subsurface pebble counts ('Wolman' and 'Buffington' methologies); and wet/dry sieving especially for the subsurface sampling. There are three main draw-backs to using the sieve method: large sample sizes, wet samples, and the problems with surface armoring. First, the size of the sample required for sieving is related to the size of the particles in the channel. According to Church et al. (1987) the sample size required is based on the largest subsurface grain and is determined by allowing the weight of that grain to comprise only 1% of the total sample weight. Since we sampled mountain streams that have large particles (sometimes small boulders) the unbiased sample size required is often unmanageable or extremely time consuming to process. Secondly, due to the relationship between sample size and weight, not only is determining a correct sample size difficult with water in the sample, but acquiring and processing the sample is difficult. Wet sieving is not possible for the small sediment, since fine sediment often clumps. Therefore the wet samples need to be dried or at least partially dried, which may require time consuming laboratory work. And third, sampling only the surface particles in a representative manner is very difficult since armored layers may only be one grain size deep and larger particles may be extensively buried.

The 'Wolman' and 'Buffington' methologies are fast, differentiate well between surface and subsurface samples, and all the data are acquired in the field. Using the pebble count method, Brush (1961) found that there was little difference in results obtained between different operators and indicated that 60 particles is the smallest number necessary to give reproducible results. However, Leopold et al. (1964) suggest that a sample size of 100 pebbles is more appropriate for streams flowing over gravel. The greatest draw-back to this method is the inability to adequately

measure fine sediment, <4 mm (Leopold et al., 1964) or very large sediment (Church et al., 1987). However, our data indicate that calculated surface median grain sizes are relatively insensitive to the proportion of fine sediment sampled in each reach. Although the maximum grain size accurately measurable using these methods is boulder sized (Church et al. 1987), few of reaches contained such large sediment sizes.

Land Use

In Finney Creek, local characteristics such as channel slope and depth did not appear to influence sediment size and armoring, whereas in Boulder River, both local and watershed scale features, such as channel slope and drainage area, influence sediment characteristics. Since Finney Creek and the Boulder River watersheds share a drainage divide, the climatic environment should be similar, and since they also share a similar geologic history, the most influential difference between these two watersheds is land use. Data from the Finney Creek watershed, which is a tree farm, indicate that relationships between sediment characteristics and hydraulic characteristics are poor, but relationships from Boulder River, an unmanaged watershed, do not support those findings. A partial explanation for these differences may be the relative positions of sediment sources in each watershed. Mass wasting events occur throughout the Finney Creek watershed, while mass wasting in the Boulder River watershed comes from above tree line and/or from active glaciers, both of which are in the extreme headwaters of the basin. Another explanation is that Finney Creek channels have more sediment due to the abundance of local sediment sources. Local sediment sources provide a supply of fine sediment, which decreases the opportunity for the development of an armored surface layer. These scenarios as well as others could explain the differences found between the Boulder River and Finney Creek data. Unfortunately, it is unclear if one of these scenarios or another one could cause the same difference between these two data; additional data are needed to clarify mechanisms contributing to these differences.

One noticeable feature of the Finney Creek data is the higher amount of fine sediment sampled in the surface counts (Figure 6) than in the other Washington watersheds. Both the range

and the median differ between surface fines found in Finney Creek and in the Boulder River. Since armored layers typically do not develop in stream beds that are over-loaded by sediment, one potential scenario could be that the managed channels of Finney Creek have relatively higher sediment supplies than their non-managed counterparts in the Boulder River. The higher sediment amounts in Finney Creek may indicate that either there is more fine sediment, or that Finney Creek is not selectively transporting fine sediment. Reviewing the SF Hoh River data, there is no obvious difference in surface fine sediment between managed and pristine reaches. In contrast, comparisons in the median amount of subsurface fines indicate that reaches in managed watersheds have more fine sediment than unmanaged watersheds.

Coos Bay Watersheds

The most noticeable difference between the Coos Bay watersheds and the others occurs with the unusually high amount of fine sediment in the subsurface data. As this bedrock is weak marine sediment, the smaller clast size is expected. Unlike the other watersheds, these river valleys were not glaciated; therefore sediment found in the channels was derived only from the Tyee Formation, which creates an obvious source for fine sediment. Based on these data, the amount of subsurface fine sediment found in a river is as much a function of geology as land use.

Implications

The influence of wood debris on the transport of sediment is difficult to predict and is not incorporated in the models supporting the comparisons presented above. Although there may be correlations between grain size and hydraulic features in forced alluvial channels, we do not necessarily expect simple relationships. Buffington (1995) found that surface textures of in-channel deposits and their response potential are controlled by the roughness provided by the in-channel structures, which is highly variable from reach to reach. The impact to channel form and sediment transport from wood depends on the debris characteristics (e.g., size, orientation, and positions) and channel conditions (e.g., size and confinement). Since the study reaches selected for this study were mostly wood-free, our data cannot address relationships between surface grain

size and hydraulic features in forced alluvial channels. Note that LWD could strongly effect such relations.

A relationship between bed-surface grain size and channel features reflects hydraulic sorting, however, subsurface data indicates that channel conditions or characteristics do not influence grain size. These findings are consistent with hypotheses and data presented by Montgomery and Buffington (1997). Hence, single values of the degree of armoring (d_{50s}/d_{50ss}) reveal more about local hydraulics than about channel conditions or sediment supply. In both managed and pristine landscapes, such ratios need to be interpreted in the context of watershed-wide patterns.

CONCLUSIONS

In contrast to the classical expectation of downstream fining, our surface grain size data from headwater channels increase downstream, with surface grain size roughly correlated to local hydraulic variables. Of course, grain size distributions must eventually switch to fining downstream, but our results suggest that a hydraulic control on bed surface grain-size distribution is a fundamental aspect of headwater streams in mountain drainage basins. Variations in sediment supply caused by altering the volume of sediment or by changes in the rate of movement due to wood debris, especially on the local scale, can significantly affect the relations with hydraulic features discussed above. The strong patterns documented here indicate that great care needs to be applied when using the simple ratio of d_{50s}/ d_{50ss} as a channel assessment methodology.

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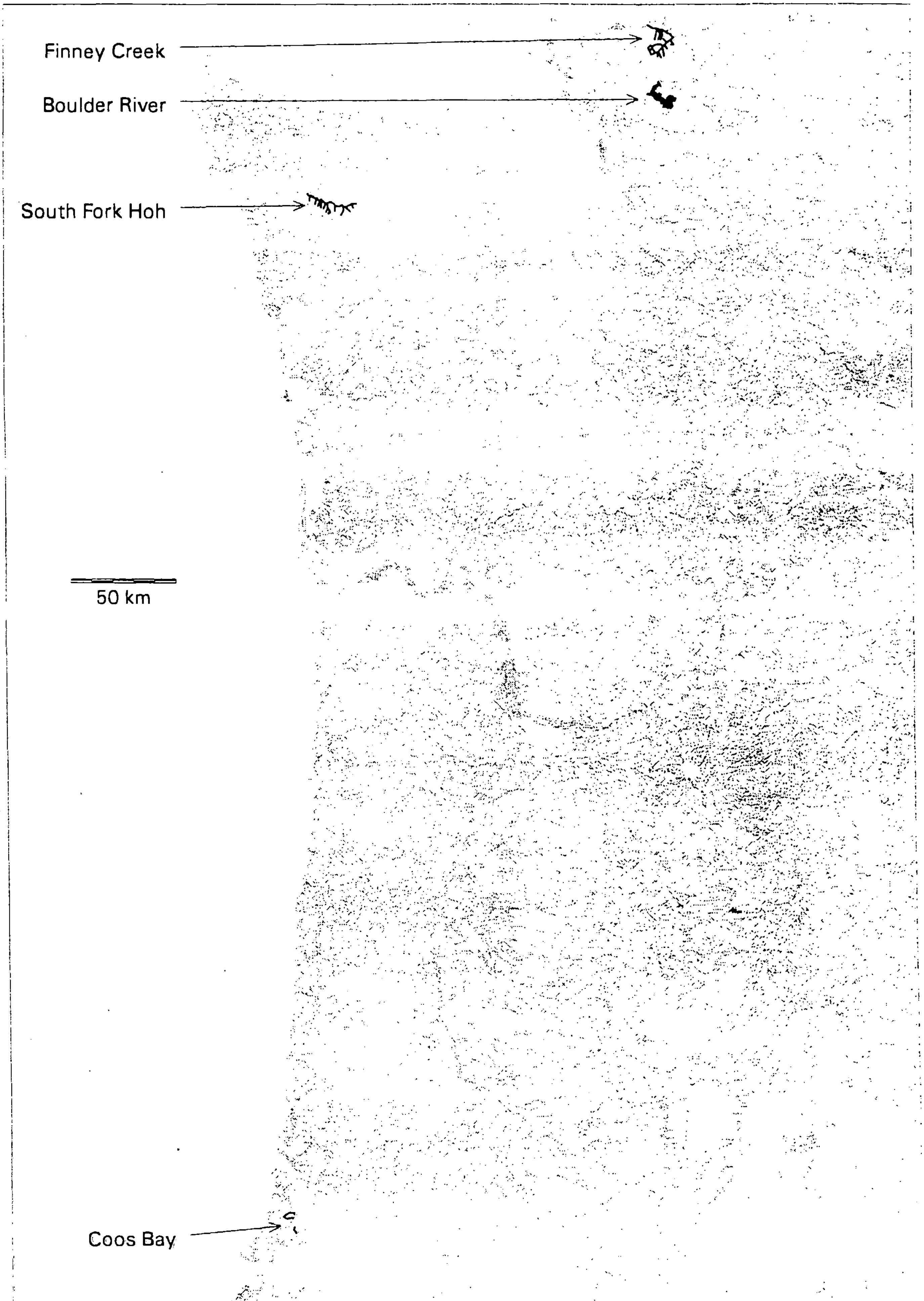
Figure List


Finney Creek
Boulder River
South Fork Hoh
50 km
Coos Bay

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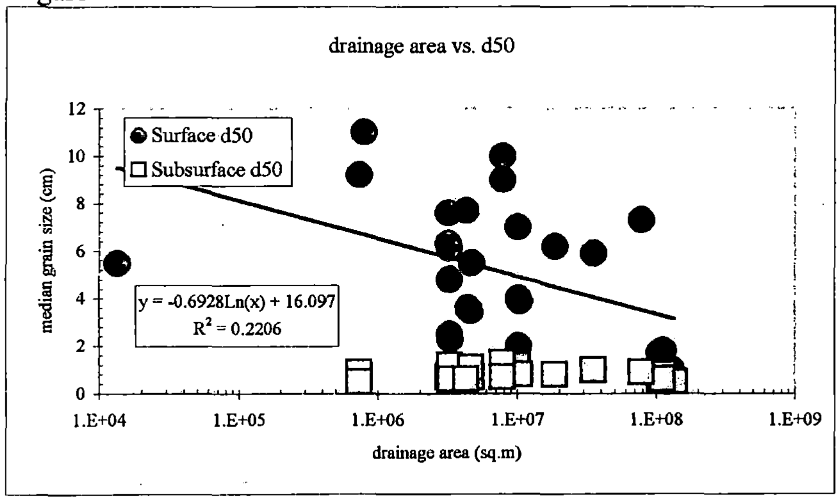

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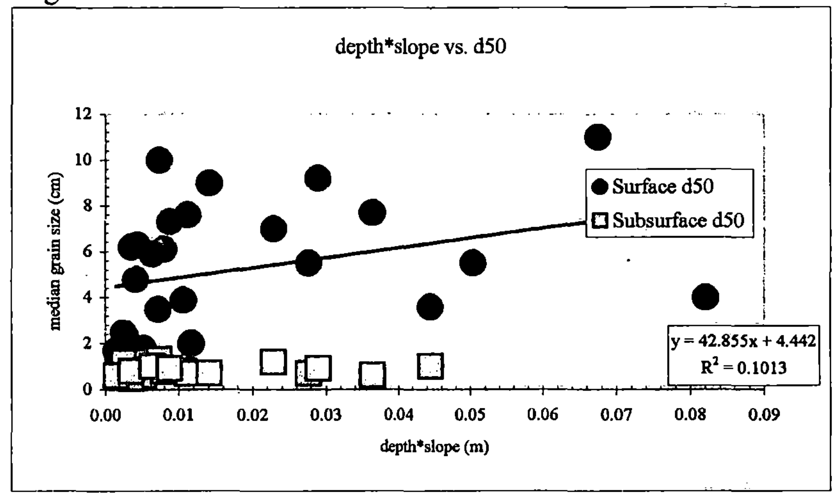

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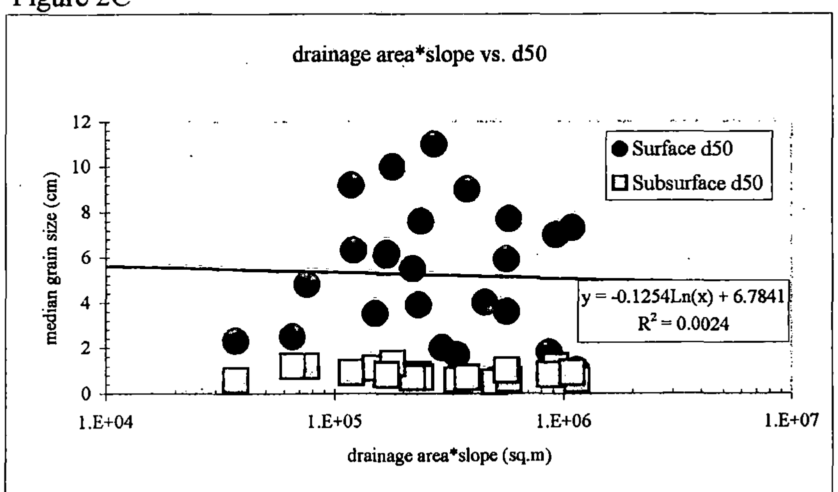

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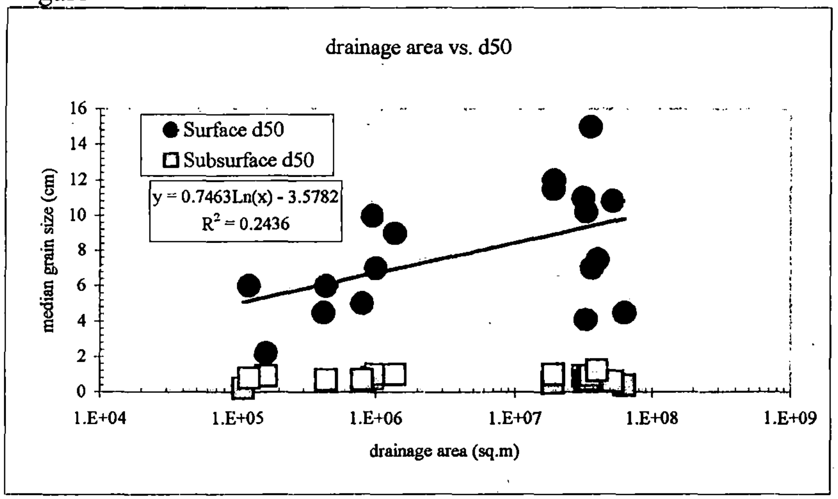

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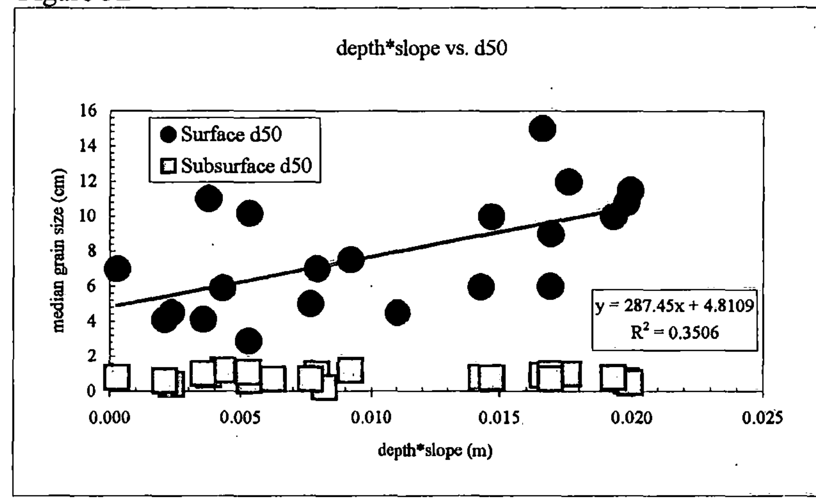

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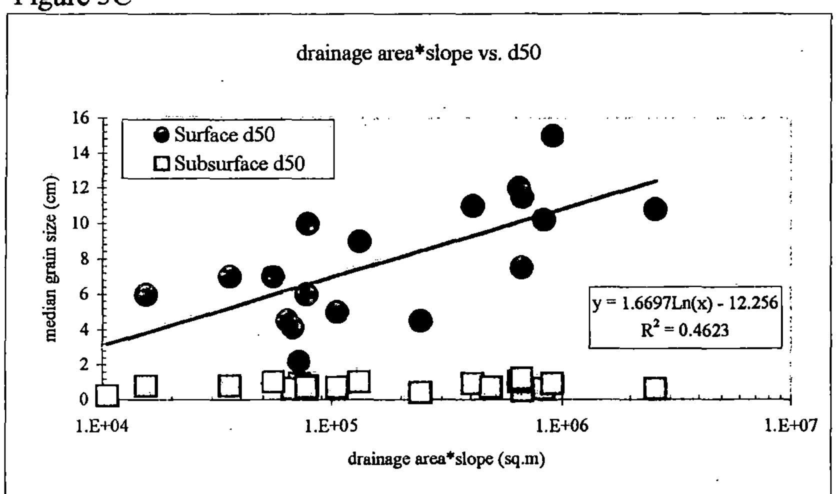

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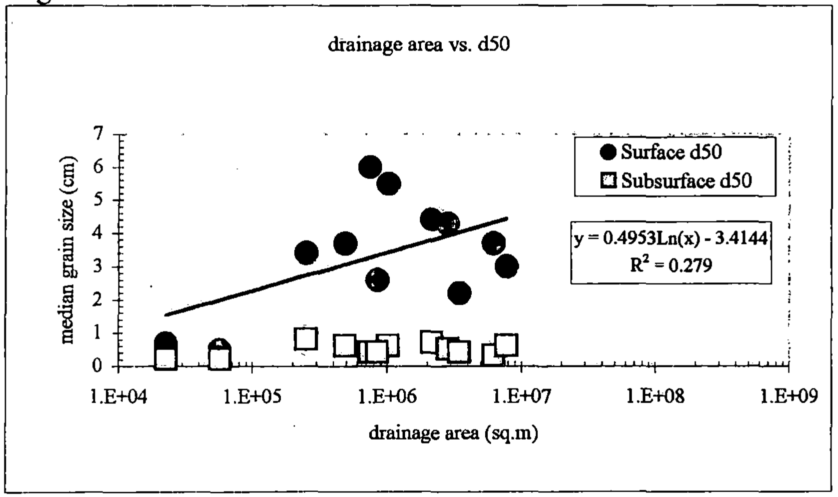

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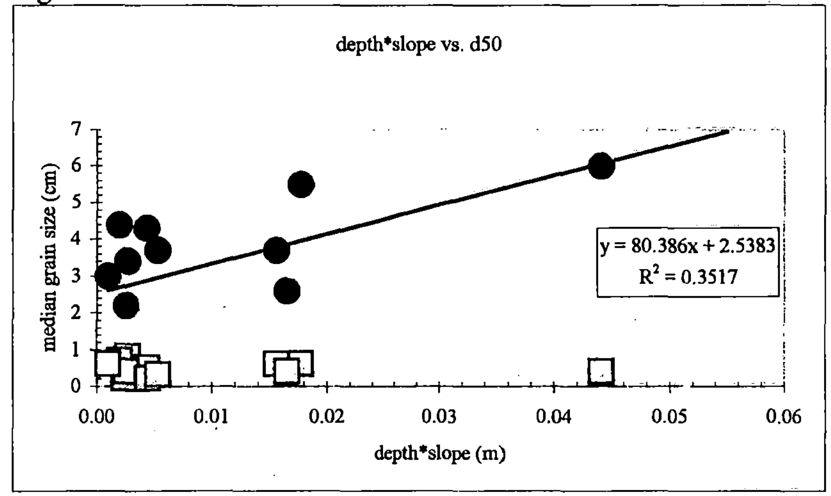

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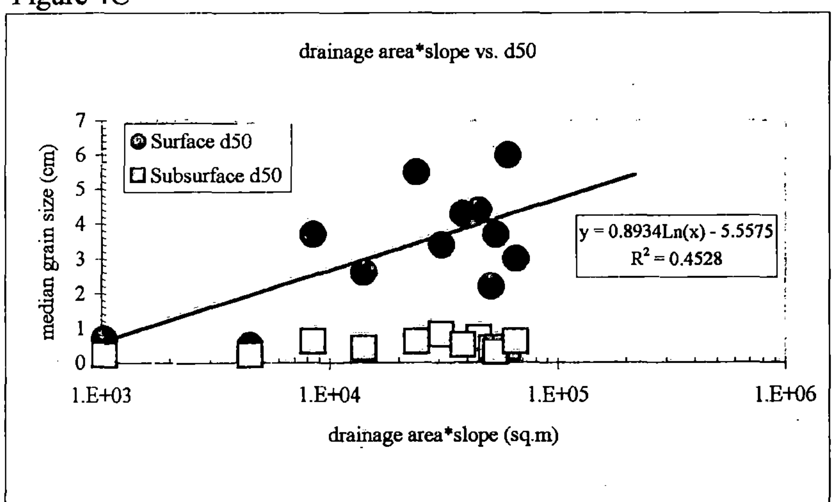

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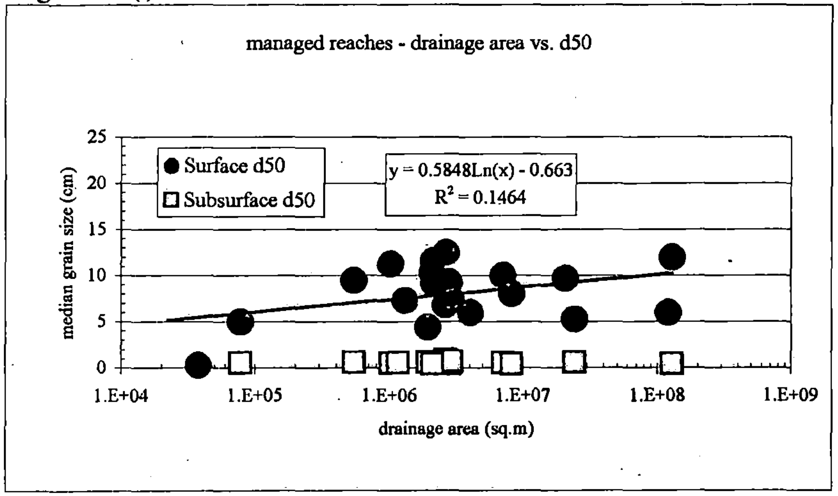

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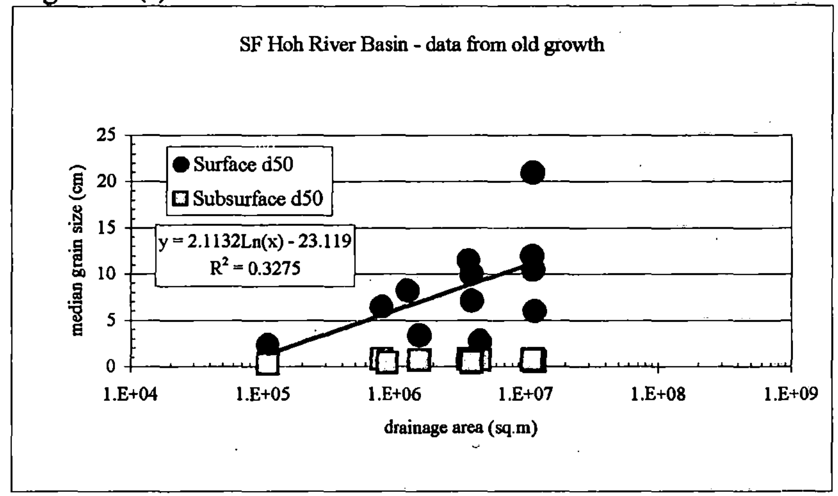

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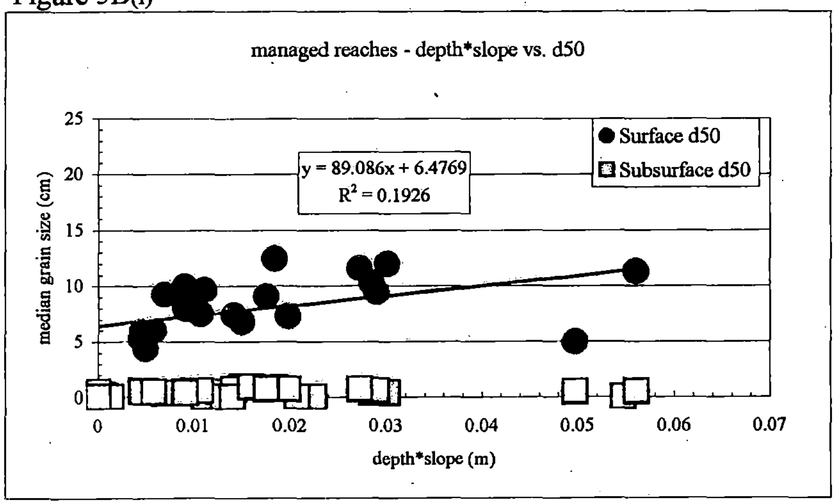

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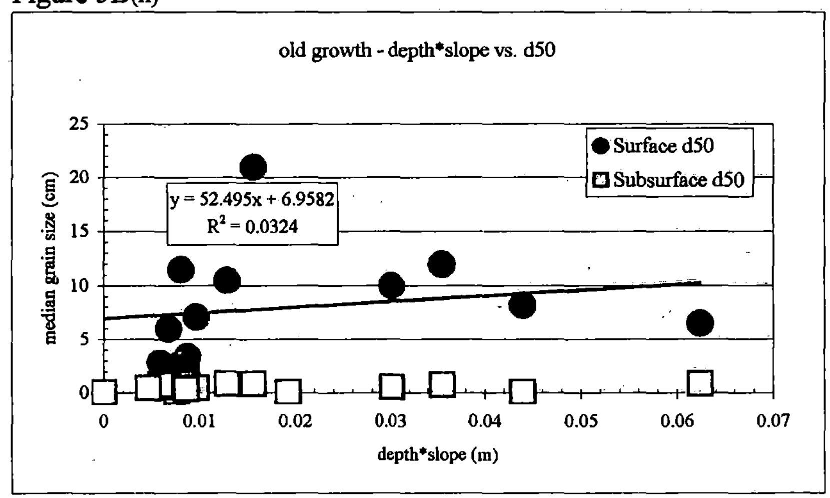

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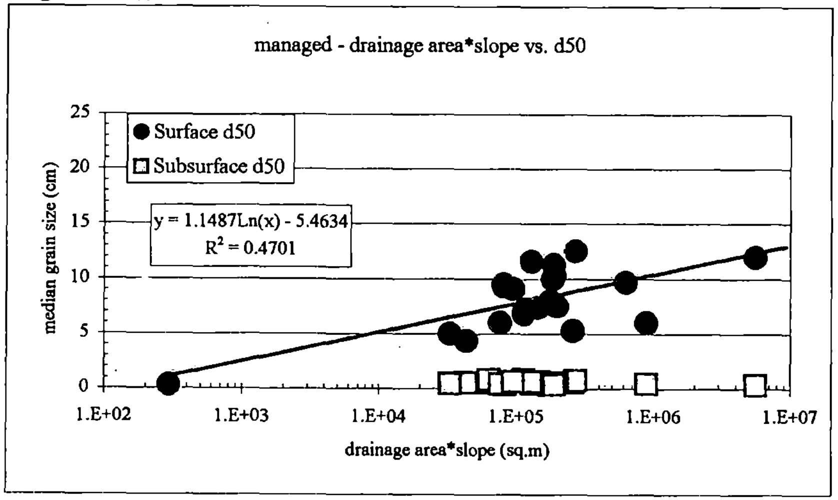

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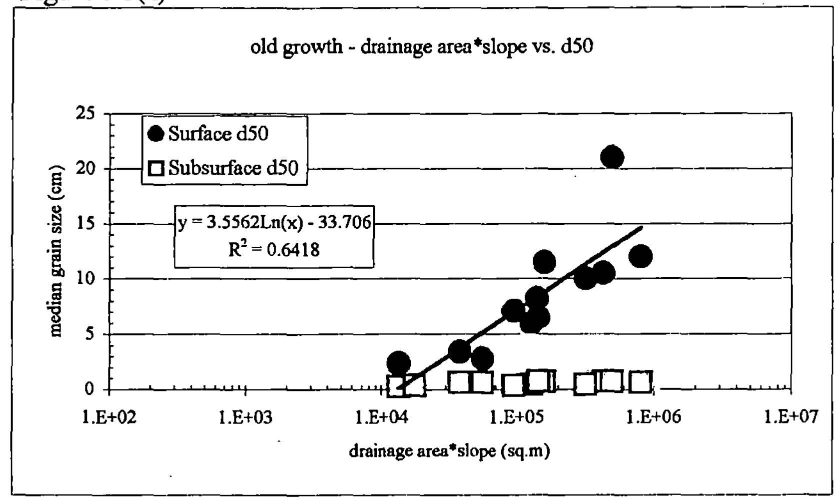

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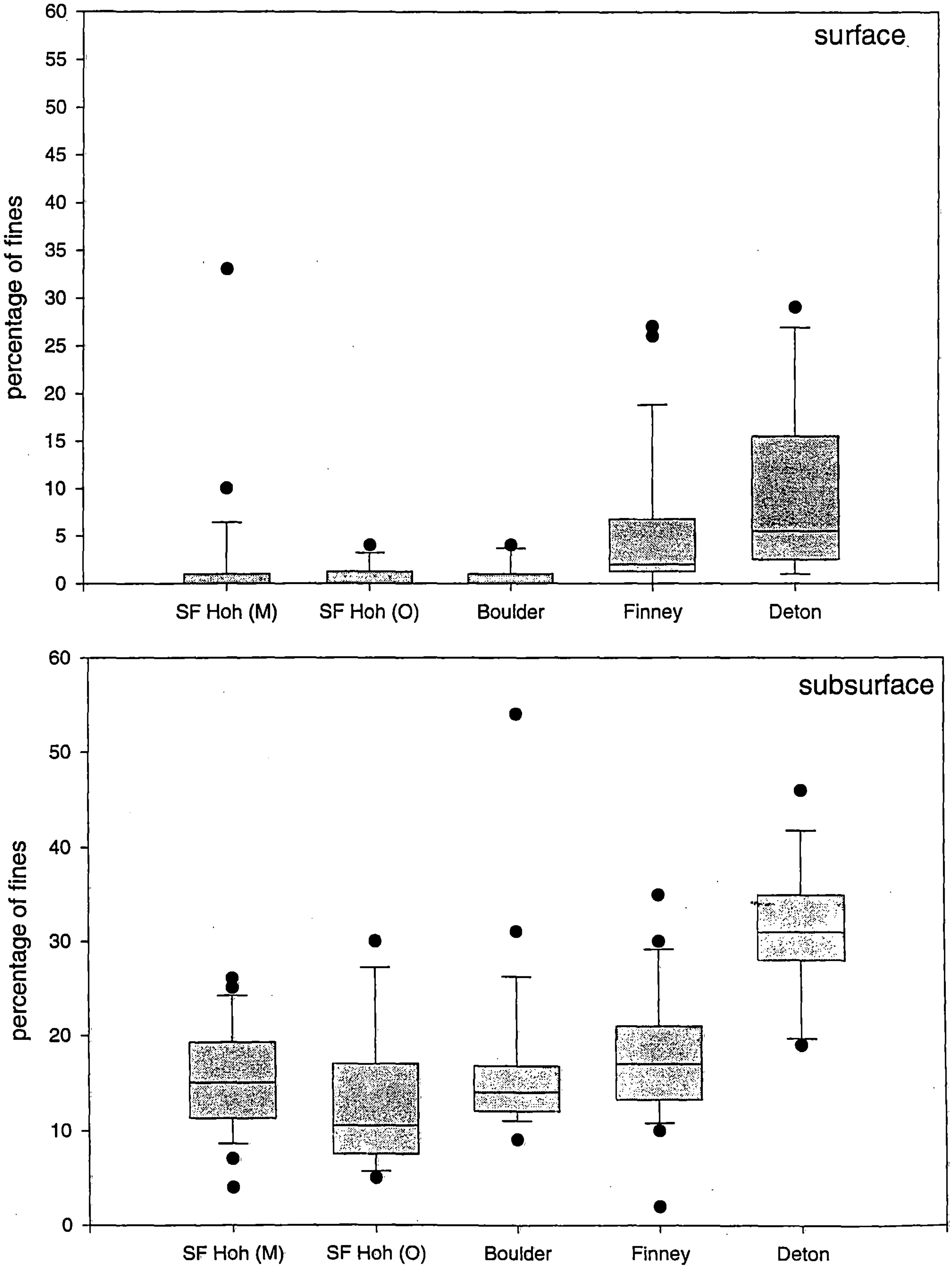

surface
percentage of fines
0
5
10
15
20
25
30
35
40
45
50
55
60
SF Hoh (M)
SF Hoh (O)
Boulder
Finney
Deton
subsurface
percentage of fines
0
10
20
30
40
50
60
SF Hoh (M)
SF Hoh (O)
Boulder
Finney
Deton

Figure 7A

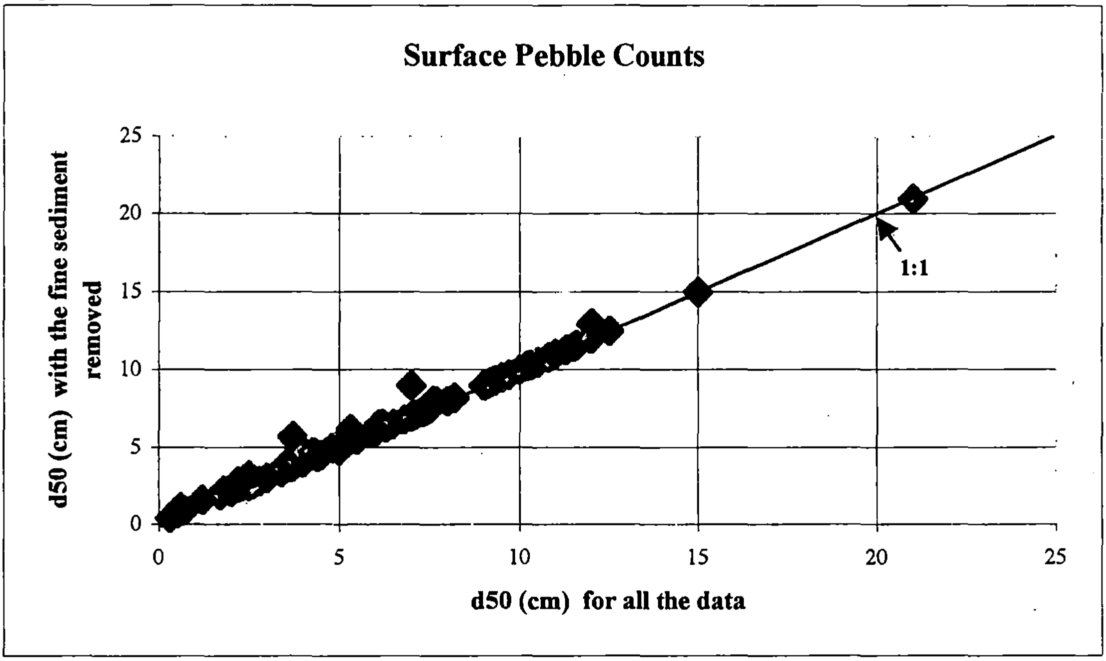


Figure 7B

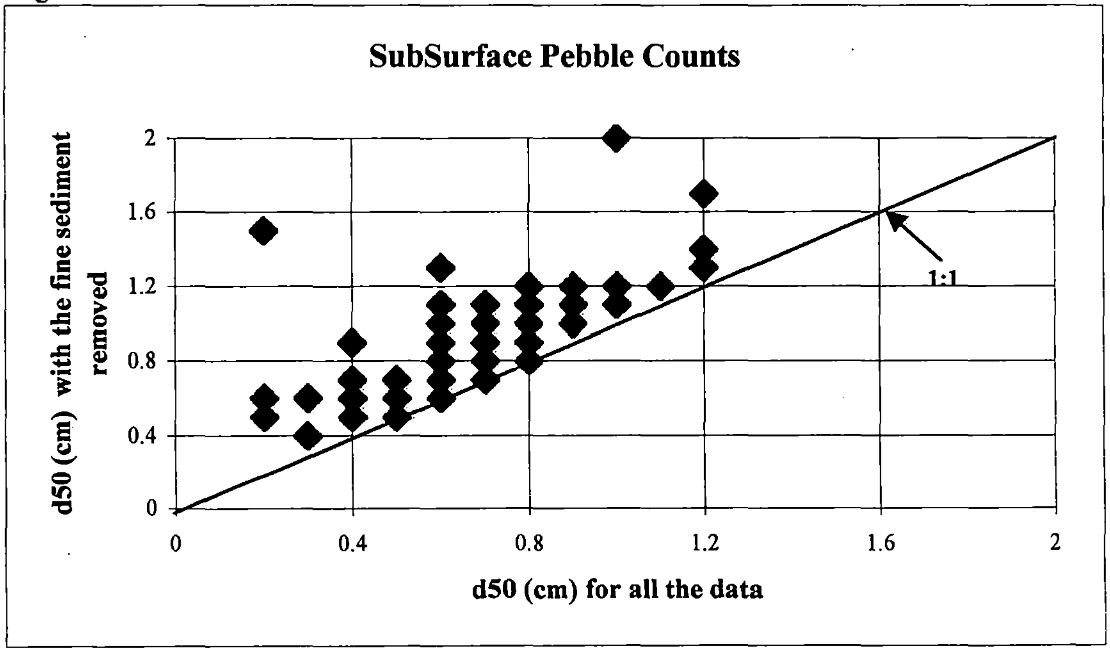
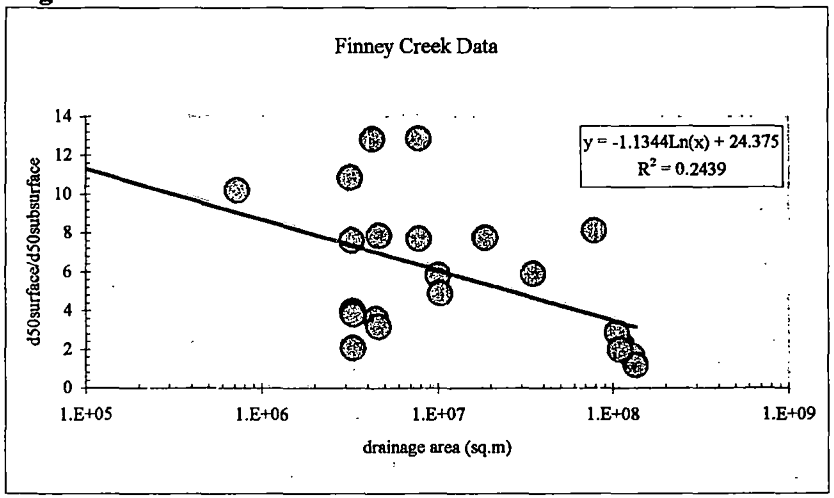


Figure 8A



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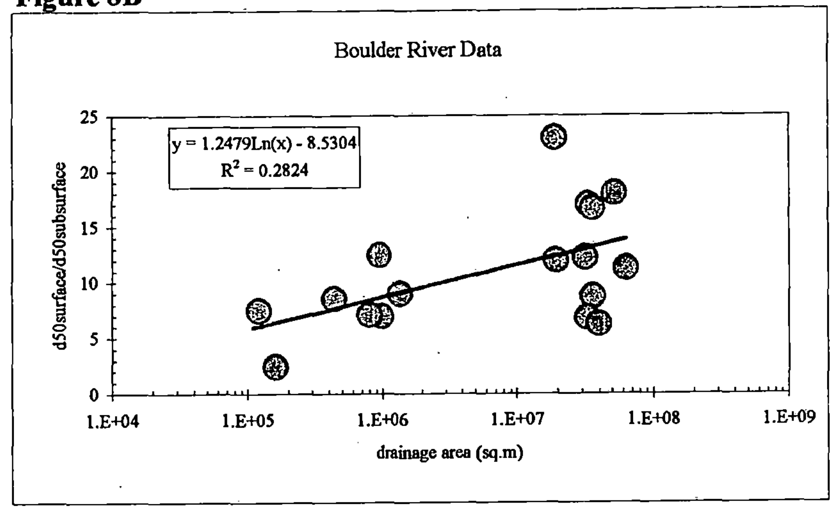

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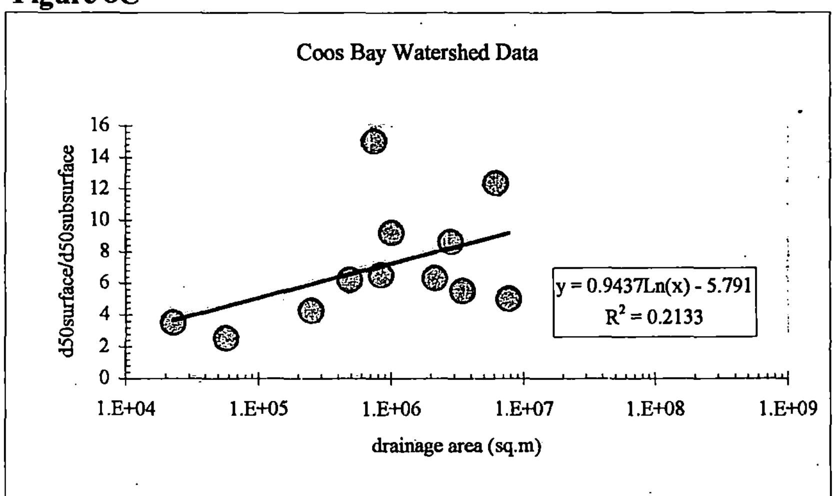

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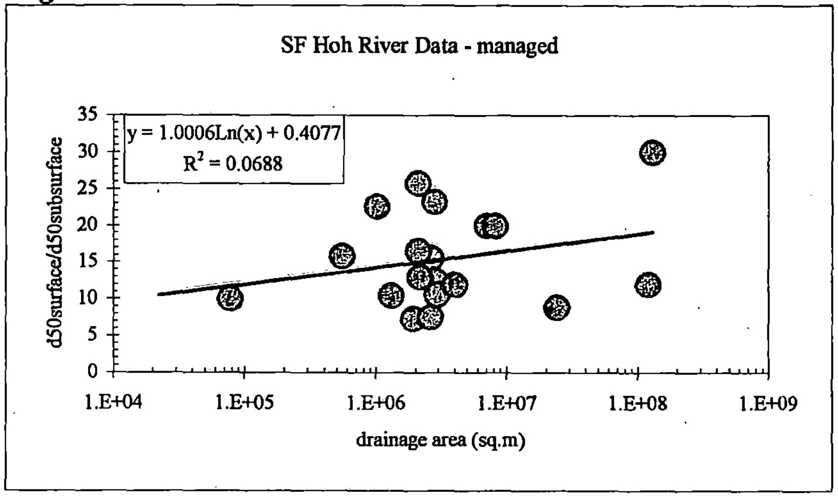

Figure 8E